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Deep subwavelength photonic multilayers fabricated by atomic layer deposition

Evgeniy Shkondin [a,b], Sergei V. Zhukovsky [b,c], Andrei A. Andryieuski [b], Osamu Takayama [b], Radu Malureanu [b] , Mikkel Dysseholm Mar [a], Andrei Lavrinenko [b], Flemming Jensen [a]

[a] DTU Danchip - National Center for Micro- and Nanofabrication, Kgs. Lyngby, 2800, Denmark
[b] DTU Fotonik – Department of Photonics Engineering, Kgs. Lyngby, 2800, Denmark
[c] ITMO University, St. Petersburg, 197101, Russia

eves@fotonik.dtu.dk

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Photonic dielectric multilayers are one of the most studied systems in optics [1]. Applications include Bragg mirrors, antireflection coatings, band–pass filters etc. Research traditionally focused on layered structures with thicknesses *d* compared to the wavelength of light λ and omitted much thinner layers. It was commonly assumed that the description of such deep ($d \ll \lambda$) subwavelength multilayers is governed by effective media approximation (EMA) theory [2]. However recent theoretical publications [3], [4] suggest that EMA assumption may fail if the angle of incidence is close to the angle of total internal reflection. The transmission spectrum in this case becomes different than predicted by EMA. The spectrum becomes sensitive to layers thicknesses on nanometer scale and their order in multilayer. Moreover the EMA breakdown effect can be enhanced by placing the multilayer in photonic resonator set-up [4] as it shown in Fig 1. In this work we present the fabrication approach to the described structure.

TiO_2 and Al_2O_3 metal oxides were selected as the multilayer components and silicon nitride (Si_3N_4) as photonic resonator. The fabrication of the multilayers was performed in a commercial hot-wall ALD system (Picosun R200, Finland). The precursors used for Al_2O_3 and TiO_2 deposition were trimethylaluminum $Al(CH_3)_3$ and titanium tetrachloride ($TiCl_4$), respectively. An oxidant source in both processes was deionized water. The deposition temperature was chosen at 120C in order to prevent the crystal anatase phase transition of TiO_2 known to occur at temperatures above 150C [5]. Such transition would increase the films roughness. To establish the deposition rate, Al_2O_3 and TiO_2 films with thickness ranging between 10 and 50 nm were deposited on Si substrates, with subsequent ellipsometric characterization of the films thicknesses and refractive indices. It was determined that TiO_2 and Al_2O_3 have a constant growth rate of 0.047 and 0.089 nm/cycle respectively.

The substrates for the samples were fabricated by depositing 1 µm of Si_3N_4 (the resonator layer) on 100 mm silicon < 100 > wafers using low-pressure chemical vapor deposition. The process was carried out at 780C with ammonia (NH_3) and dichlorosilane (SiH_2Cl_2) as reactive gases. Thickness and refractive index of the deposited silicon nitride was measured and confirmed using spectroscopic ellipsometry. The deposited Si_3N_4 film was carefully analyzed for existence of cracks, particles and other defects using dark field optical microscopy. The best-quality wafer with Si_3N_4 was selected and cleaved in pieces, which were used as substrates for the deposition of Al_2O_3/TiO_2 multilayers. Before inserting each substrate into the ALD reactor, it was placed on a Si carrier wafer. Therefore the Al_2O_3/TiO_2 multilayers were grown not only on the Si_3N_4 layer but also on the dummy carrier wafer. After the ALD process was completed, the dummy was cleaved and its cross-section was characterized using scanning electron microscopy (SEM). The SEM images reveal high-quality homogeneous, conformal coatings, as seen in the examples in Figs 2 and 3. Such a method of deposited multilayers characterization turned out to be more feasible than the direct SEM characterization of multilayers on Si_3N_4, since the latter suffers from issues related to charge accumulation on the silicon nitride.

We believe this fabrication flow opens possibility for experimental demonstration of EMA theory breakdown in deep subwavelength multilayers.

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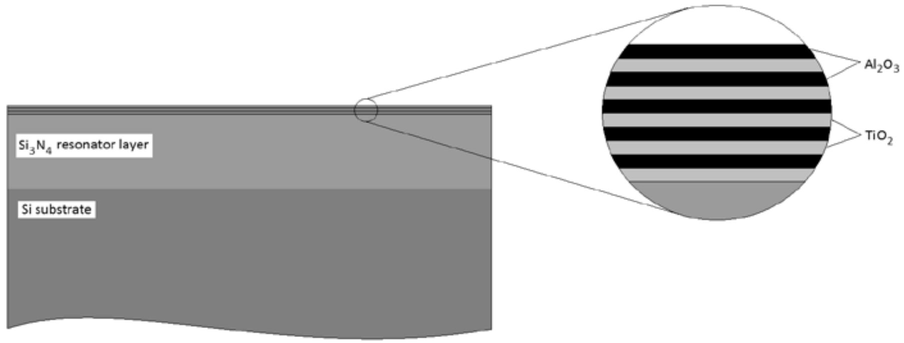

Figure 1. System schematics. Subwavelength Al_2O_3/TiO_2 multilayer is placed on Si_3N_4 photonic resonator set-up.

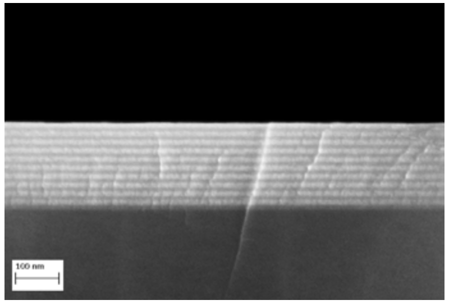

Figure 2. SEM image of fabricated 200 nm TiO_2/Al_2O_3 multilayer on Si substrate. Thickness of each layer is 10 nm.

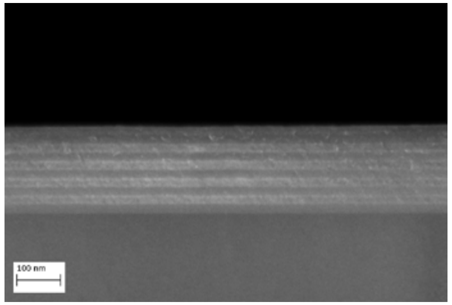

Figure 3. SEM image of fabricated 200 nm TiO_2 $/Al_2O_3$ multilayer on Si substrate. Thickness of each layer is 20nm.